

Ruelle E, Delaby L, Wallace M, Shalloo L. [Development and evaluation of the Herd Dynamic Milk Model with focus on the individual cow component.](#)

Animal 2016

Copyright:

The final version of this article is published by Cambridge University Press

DOI link to article:

<http://dx.doi.org/10.1017/S1751731116001026>

Date deposited:

28/06/2016

Embargo release date:

23 November 2016



This work is licensed under a [Creative Commons Attribution-NonCommercial 3.0 Unported License](#)

Animal: An International Journal of Animal Bioscience

Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component --Manuscript Draft--

| | |
|------------------------------|--|
| Manuscript Number: | ANIMAL-15-21063R2 |
| Full Title: | Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component |
| Short Title: | Evaluation of the herd dynamic milk (HDM) model. |
| Article Type: | Research Article |
| Section/Category: | 3. Physiology and functional biology of systems |
| Keywords: | modelling; model evaluation; Dairy cows; Milk yield; body condition score |
| Corresponding Author: | Elodie Ruelle, Ph.D. Teagasc Moorepark Fermoy, Cork IRELAND |
| First Author: | Elodie Ruelle, PhD |
| Order of Authors: | Elodie Ruelle, PhD Luc Delaby Michael Wallace, PhD Laurence Shalloo, PhD |
| Manuscript Region of Origin: | IRELAND |
| Abstract: | <p>The Herd Dynamic Milk model (HDM) is a dynamic model capable of simulating the performance of individual dairy animals (from birth to death), with a daily time step. Within this study the HDM model is described and evaluated in relation to milk production, body condition score (BCS) and BCS change throughout lactation by comparing model simulations against data from published experimental studies. The model's response to variation in genetic potential, herbage allowance and concentrate supplementation was tested in a sensitivity analysis. Data from experiments in Ireland and France over a 3 year period (2009 to 2011) were used to complete the evaluation. The aim of the Irish experiment was to determine the impact of different stocking rates (SR) (SR1: 3.28 SR2: 2.51 cow/ha) on key physical, biological and economic performance. The aim of the French experiment was to evaluate over a prolonged time period, the ability of two breeds of dairy cows (Holstein and Normande) to produce and to reproduce under two feeding strategies (high level and low level) in the context of compact calving. The model evaluation was conducted at the herd level with separate evaluations for the primiparous and multiparous cows. The evaluation included the two extreme stocking rates for the Irish experiment, and an evaluation at the overall herd and individual animal level for the different breeds and feeding levels for the French data. The comparison of simulation and experimental data for all scenarios resulted in a relative prediction error, which was consistently lower than 15% across experiments for weekly milk production and BCS. In relation to BCS, the highest root mean square error was 0.27 points of BCS which arose for Holstein cows in the low feeding group in late lactation. The model responded in a realistic fashion to variation in genetic potential for milk production, herbage allowance and concentrate supplementation.</p> |

Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component

E. Ruelle^{1,2}, L. Delaby³, M. Wallace⁴ and L. Shalloo¹

¹*Teagasc, Animal and Grassland Research and Innovation Centre, Moorepark, Fermoy, Co. Cork, Ireland*

²*School of Agriculture and Food Science, University College Dublin, Belfield, Dublin 4, Ireland*

³*INRA-Agrocampus-Ouest, UMR 1348, Physiologie, Environnement et Génétique pour l'Animal et les Systèmes d'Elevage, Domaine de la Prise, 35590 Saint Gilles, France.*

⁴*School of Agriculture, Food and Rural Development, Newcastle University, Newcastle upon Tyne, NE1 7RU, United Kingdom*

Corresponding author: Elodie Ruelle Email: elodie.ruelle@teagasc.ie

Short title: Evaluation of the herd dynamic milk (HDM) model.

Abstract

The Herd Dynamic Milk model (HDM) is a dynamic model capable of simulating the performance of individual dairy animals (from birth to death), with a daily time step. Within this study the HDM model is described and evaluated in relation to milk production, body condition score (BCS) and BCS change throughout lactation by comparing model simulations against data from published experimental studies. The model's response to variation in genetic potential, herbage allowance and concentrate supplementation was tested in a sensitivity analysis. Data from experiments in Ireland and France over a 3 year period (2009 to 2011) were used to complete the evaluation. The aim of the Irish experiment was to determine the impact of different stocking rates (**SR**) (SR1: 3.28 SR2: 2.51 cow/ha) on key physical, biological and economic performance. The aim of the French experiment was to evaluate over a prolonged time period, the ability of two breeds of dairy cows (Holstein and Normande) to produce and to reproduce under two feeding strategies (high level and low level) in the context of compact calving. The model evaluation was conducted at the herd level with separate evaluations for the primiparous and multiparous cows. The evaluation included the two extreme stocking rates for the Irish experiment, and an evaluation at the overall herd and individual animal level for the different breeds and feeding levels for the French data. The comparison of simulation and experimental data for all scenarios resulted in a relative prediction error, which was consistently lower than 15% across experiments for weekly milk production and BCS. In relation to BCS, the highest root mean square error was 0.27 points of BCS which arose for Holstein cows in the low feeding group in late lactation. The model responded in a realistic fashion to variation in genetic potential for milk production, herbage allowance and concentrate supplementation.

Keywords: modelling; model evaluation; dairy cows; milk yield; body condition score

Implication

A new model has been developed which can simulate milk production and body condition score change of dairy cows through lactation under grazing conditions. For both milk production and body condition score change the model shows good accuracy. From a farmer's perspective, the model, once adapted with an user-friendly interface, can be used at individual animal level or at a herd level. Clear management practices can be tested by applying certain strategies around pasture and animal management to determine their effects on milk production and body condition score change.

Introduction

Modelling dairy systems can be complex due to the interactions between all the intrinsic components of the cow (breed, genetic potential, parity, etc) but also due to the interaction of the animal with the environment (feeding system, type of housing, time of year, stage of lactation, etc) and the management (dairy farmer decisions) to which animals are subjected (nutrition status, breeding, etc) (Buckley *et al.*, 2003, Martin and Sauvant, 2010a). A model if useful must be capable of simulating all of the components of a system in a realistic fashion and the model must be capable of reacting to the changing components of the system. The ever increasing pressures placed on farmers due to changing circumstances (e.g. milk price volatility and climate change) means that there is increased pressure with all decisions taken on the farm. Having a model that can react in a meaningful way across these different questions allows farmers to optimise their decision making process continually. For

example, when feeding the dairy cow, predicting the partition between milk production and body condition score change throughout lactation either in grazing or indoor feeding would allow better decisions to be made on farm but these challenges present a major obstacle for modelers all over the world (Friggens *et al.*, 2004, Faverdin *et al.*, 2011, Baudracco *et al.*, 2012). The model presented here deals with this issue in a grazing context.

A key feature in the development of a model is the evaluation and validation step. The most common way to validate a model is to compare with existing experimental data. The E-Cow model Baudracco *et al.* (2012) has been evaluated using two independent experimental datasets from New-Zealand and Argentina. The statistical analyses used were the concordance correlation coefficient (**CCC**) and the relative prediction error (**RPE**) to evaluate the daily herbage dry matter intake, the milk yield and live weight change. The milk production and herbage intake of the French model GrazIN (Delagarde *et al.*, 2011a, Faverdin *et al.*, 2011) was validated by comparing model outputs against experimental data using the mean square prediction error on 206 experimental herds (Delagarde *et al.*, 2011b).

The objective of this paper was to present and evaluate a new model in terms of milk production and BCS prediction. The strength of this model lies on an update of the idea of the partition of the energy and protein intake between the milk production and the body reserve in pasture based systems (Bruce *et al.*, 1984). The goal was to integrate the genetic progress and its consequences in terms of intake, BCS change in the partition of the nutrient intake depending on the lactation stage and the genetics of the animal. Data from two different studies in two different countries (Ireland and France) which operate grass based systems of differing levels of intensity and supplementation were used to evaluate the model. The model has also

been evaluated on its ability to respond to changes in genetics of the animals, herbage allowance and concentrate supplementation with outputs compared to expected outputs based on published literature.

Materials and methods

The Herd Dynamic Milk model (**HDM**) is a dynamic model developed in C++ capable of simulating the performance of dairy animals (from birth to death) individually, with a daily time step. Briefly, the model allows differentiated management of different groups of animals (mainly through feeding). The groups included are calves (0 – 90 days), three groups of heifers (90 days to 365 days, 12 to 24 months and over 24 months), lactating cows and the dry cows. Each animal is simulated individually permitting a precise representation of each animal on the farm. At calving, the dam (heifer or cow) is transferred from the heifer or dry cow group to the lactating cow group and one or two calves are added to the calf groups depending on the prolificacy (adjusting for mortality). This paper will describe in detail the cow component of the model during lactation in terms of milk production and BCS change. The young stock, dry cow, fertility and mortality aspect are described in the supplementary material. A flow diagram of the lactation element of the model is presented in Figure 1.

Figure 1 around here

Inputs and Outputs of the model

The initial herd demography is specified via the description of the individual animals presented at the start of the simulation. The information required for every animal is age (day); body weight (**BW**) (kg); theoretical potential maximum milk yield (kg/d) for

the calf (used when she becomes a cow), heifer and cow; as well as the day in gestation and the number of inseminations (since the last calving for the cows) for the heifer and cow; and finally the day in lactation and the BCS and BCS at calving for the cow. The BCS scale used within this model is the 0 to 5 scale (Bazin *et al.*, 1984). The theoretical potential maximum milk yield is defined as the theoretical maximum daily milk production of the mature cow (parity 3 and more) at peak of lactation with a static BCS and BW. The period of simulation is expressed in monthly time blocks and can be from one month to at least in theory an infinite time. The initialisation of the model also requires the user to input key management decisions which include the maximum number of animals on farm, information about insemination (breeding period; maximum number of inseminations), dry off (specific date or day in lactation) and culling criteria. In terms of feeding, the herbage allowance, feed energy and protein content are needed as well as allocation of supplementary feed whether concentrate or forage. The main daily outputs of this model are the dry matter intake, milk production, BCS and BW for every animal for everyday of the year. These outputs can be summarised for the cattle by week of lactation or by week of the year. The total milk produced per cow per lactation is also available.

Herd feeding and dairy cow performance

The model incorporates the French feeding system (Faverdin *et al.*, 2010, Faverdin *et al.*, 2011) which was modified to integrate milk production, BCS and BCS change of animals. In this paper, the milk output from the model is expressed in kg of standard milk (**MY**) at 4.0 % of fat and 3.1 % of protein content, corresponding to the equation of Faverdin *et al.* (2010) (Supplementary Equation S12).

Intake and nutrient supply. The INRA feeding system (INRA, 2010) was selected to model the nutrient intake within the model. The intake when housed and at grazing is calculated based on the GrazeIn model as described in (Delagarde *et al.*, 2011a, Delagarde *et al.*, 2011b, Faverdin *et al.*, 2011). In simple terms, intake of the animal is the lesser of the intake permitted by the intake capacity and fill value of the feed, the herbage allowance and the intake needed to meet the requirements. The intake at grazing is calculated depending on the possible intake of the housed animal corrected for herbage allowance and time at pasture. The quality of the forage or grass is characterised by its energy value (**UFL** "unité fouragère lait"), protein (**PDI** "protéine digestible dans l'intestin) and **FV** (Fill Value). The FV of a forage is an inverse function of its ingestibility and is calculated by the ratio of intake of the reference forage to voluntary dry matter intake of the considered forage (Faverdin *et al.*, 2011). The quality of the concentrate is determined by its UFL and PDI. The concentrate has no fixed FV, its FV is calculated dependent on the substitution rate between concentrate and forage which represents the metabolic regulation of intake and depends on the percentage of concentrate and the total energetic value of the diet (Faverdin *et al.*, 2011).

Calculation of the theoretical milk yield (theoMY) and maximum theoretical Mobilisation (theoMOBmax). In this model, the BCS change and the milk yield are modelled together in an interlinked way depending on the interaction between the nutrient, feed intake and partition. These two components depend mainly on two factors:

Factor 1 - A BCS pool at calving (**theoMOBmax**), expressed in units of BCS. This BCS pool gives the theoretical maximum mobilisation of the dairy cow through the lactation,

Factor 2 - The gap (**MYgap**) between the theoretical milk yield of the cow and the milk yield allowed by her energy intake, expressed in kg of milk.

The theoretical milk yield of the cow is driven by her maximum theoretical milk yield (**theoMYmax**), expressed in kg of standard milk and is dependent on the parity and the day of lactation (**LacD**):

$$theoMY = coeff_parity \times theoMYmax \times (0.27 + 6.47 \times e^{-0.013 \times LacD} - 6.20 \times e^{-0.017 \times LacD}) \quad (1) \text{ for primiparous,}$$

$$theoMY = coeff_parity \times theoMYmax \times (0.25 + 2.95 \times e^{-0.015 \times LacD} - 2.70 \times e^{-0.028 \times LacD}) \quad (2) \text{ for multiparous.}$$

With $coeff_parity=0.75$ for parity 1, 0.92 for parity 2 and 1 otherwise (Hutchinson *et al.*, 2013).

The shape of the lactation profiles originates from a previous study of Masselin *et al.* (1987) which described many classical lactation curve models based on the **theoMYmax**. The **theoMYmax** expresses the cow's milk production potential in terms of her estimated yields at peak lactation in the third parity. The equations have then been adjusted using previously published data from INRA (Delaby *et al.*, 2009) and Teagasc (Horan *et al.*, 2004). Those data originates from experiments where cows spend most of their lactation at grazing.

The **theoMOBmax** (equation 3), which is the maximum possible BCS change through the lactation, is set at calving and is always negative. The equation was developed by Delaby *et al.* (2010a) for different breeds. It has been calculated using

data with a large range of BCS loss and *theoMYmax* for primiparous and multiparous cows (Delaby *et al.*, 2010a):

$$theoMOBmax = 2.2 + parity - 0.047 \times theoMYmax \times coeff_parity - 0.51 \times BCS_{calv} \quad (3)$$

with parity = -0.1 for primiparous and + 0.1 for multiparous, *BCS_calv* the BCS of the cow at calving and the *theoMOBmax* expressed in units of BCS and *coeff_parity*=0.75 for parity 1, 0.92 for parity 2 and 1 otherwise (Hutchinson *et al.*, 2013).

Calculation of the milk yield allowed by the energy intake (uflMY). It has been shown in French studies at grazing (Hoden *et al.*, 1991) that the milk production of any one day is more influenced by the previous day's nutrition than it is by the direct feed intake on that day. This component of individual animal performance is included in the model with the milk production allowed by the diet depending on the feedstuff ingested in the two previous days (Jacquot, 2012):

$$uflMY = \frac{0.3 \times UFLint_{D-2} + 0.7 \times UFLint_{D-1} - UFLreq - E}{0.44} \quad (4).$$

With *UFLint_{D-1}* the UFL ingested the previous day, *UFLint_{D-2}* the UFL ingested two days before and 0.44 corresponding to a requirement of 0.44 UFL per kg of milk at 4 % of fat content (Supplementary Equation S12).

The UFL requirement (**UFLreq**) consists of the energy for maintenance, gestation and growth (Faverdin *et al.*, 2010) (Supplementary Equation S1 to S6). *E* is a correction factor for net energy taking into account the negative effect of feeding level and concentrate feeding level has on the organic matter digestibility and energy valorisation of the ration (Faverdin *et al.*, 2011) (Supplementary Equation S5).

The milk yield gap (**MYgap**) of the animal is the difference between the milk yield allowed by the UFL intake and the theoretical milk yield and is expressed in kg of milk:

$$MYgap = uflMY - theoMY \text{ (5).}$$

Calculation of the daily milk yield (MY). The animal response is calculated depending on the MYgap sign. When MYgap is positive then the cow has surplus energy to partition between additional milk and body condition score deposition, when MYgap is negative the cow is in deficit of energy and adjusts milk and body condition score accordingly. It is firstly assumed that the diet is well balanced in terms of PDI (PDlint/UFLint=100) (Vérité and Delaby, 2000), with PDlint and UFLint the PDI and UFL ingested during the day.

The shape of the equation 6 and 7 has been generated to take into account the fact that the responses are linked to the potential of the animal and to the available energy. Those equations have been validated based on external data from INRA in LePin (Delaby *et al.*, 2003, Delaby *et al.*, 2009)

If the energy intake is higher than the requirement for theoretical milk yield (MYgap>0), the cow is able to produce more milk than the theoretical milk yield. The extra energy is used partly to produce more milk and partly to gain body reserve (through BCS and BW gain). The milk yield response rule included is curvilinear, thus it increases with theoMY and with the MYgap based on the exponential equation:

$$bcsMYresp = MYgap \times \left[(0.57 + 0.012 \times theoMY) \times e^{-0.023 \times MYgap} \right] \text{ (6)}$$

with bcsMYresp the response in kg of milk, this response is added to the theoretical milk yield.

If the energy intake is lower than the requirement for theoretical milk yield (MYgap<0), the cow will mobilize body reserve to compensate the MYgap and will lose body reserve (if possible). The ability to mobilize will depend on the remaining pool of body condition available (**actualBCSpool**) and the stage of lactation with a higher ability of the cow to mobilize in early lactation (Faverdin *et al.*, 2010):

$$bcsMYresp = MYgap \times \left(0.75 + 0.25 \times \frac{LacD}{7} \times e^{-0.25 \times \frac{LacD}{7}} \right) \times \frac{actualBCSpool}{theoMOBmax} \quad (7)$$

with bcsMYresp being the response in kg of milk, LacD the day in lactation, with this response added to the uflMY.

After the 12th week of lactation the coefficient applied on the (actualBCSpool/theoMOBmax) is set at 0.90. This is because, after week 12, the model considers the ability to mobilize the residual pool as constant and similar to the value obtained in week 12.

In a second step, the impact of the protein content of all the feed intake on the milk yield response is represented in the model through the equation developed by Vérité and Delaby (2000):

$$pdiMYresp = -6.25 + \frac{7.55}{1 + 0.21 \times e^{-0.14 \times (PDI/UFLratio - 100)}} \quad (8)$$

with pdiMYresp the response in kg of standard milk and PDI/UFLratio equal to PDI_{int}/UFL_{int} if the gap is negative, and is equal to $(PDI_{int}/UFL_{int}) \times (uflMY/TheoMY)$ if the gap is positive.

Finally, according to the different combinations of milk gap and PDI/UFLratio, there are four situations that can occur. Resulting in the MY calculated as:

- TheoMY+max(bcsMYresp,pdiMYresp) if MYgap>0 and PDI/UFLratio>100,
- TheoMY+bcsMYresp+pdiMYresp if MYgap>0 and PDI/UFLratio <100,

- $uflMY + \max(bcsMYresp, pdiMYresp)$ if $MYgap < 0$ and $PDI/UFLratio > 100$,
- $uflMY + bcsMYresp + pdiMYresp$ if $MYgap < 0$ and $PDI/UFLratio < 100$.

BCS change. The daily change of BCS (**BCSchange**) in units of BCS is dependent on the UFL balance of the animal meaning the energy differences between UFL intake and UFL expenditure as milk, maintenance, gestation and growth (Supplementary Equation S7). If the cow is in a deficit of energy, the loss of BCS will be calculated as one unit of BCS equal to 250 UFL as described by Jouven *et al.* (2008) (Supplementary Equation S8). If the cow is in surplus of energy an equation (Supplementary Equation S10) has been developed to ensure that there is never a BCS higher than 5. It integrates the higher costs of adipose tissue deposition for a cow in high condition ($BCS > 3.5$). It is based on a basic cost of 300 UFL for one point of BCS for a cow between 1.5 and 3.5 of BCS (Jouven *et al.*, 2008). In the model every day, the BCSpool is calculated as the actual BCSpool from previous day minus the BCSchange taking into account an upper bound limit of 0 and a lower bound limit of the theoMOBmax (the theoMOBmax is always negative).

When dry, the BCS change is using the same dynamic only with the component linked to milk set at 0.

Sensitivity analysis

The model was evaluated by comparing the simulated performance under various scenarios with data available from the literature. The simulation used scenarios that systematically varied the following key components:

- (i) Milk production potential: Three different theoretical maximum milk yields: 30 kg/cow per day (**LG**), 40 kg/cow per day (**MG**) or 50 kg/cow per day (**HG**).
- (ii) Feed allowance: Three different herbage allowance (**HA**) 14 kg/cow per day, 18 kg/cow per day and 22 kg/cow per day (all assumed to be grazed to 4 cm)
- (iii) Supplementation: The addition of 0 or 4 kg of cereal based concentrate per cow per day throughout the entire lactation

This resulted in 18 different scenarios. The simulations were carried out for a full 12 month period (starting on the first of January) allowing the observation of the whole lactation. It was assumed that at the start of the simulation the parity 3 cows had a BCS at calving of $N(3.6,0.25)$, $N(3.4,0.25)$ and $N(3.2,0.25)$ for the LG, MG and HG groups, respectively (1 to 5 scale), a BW of 615 kg and that animals were dry and 208 days pregnant. The BCS parameters follow a normal distribution as described by Geweke (1991): $N(\text{average}, \text{standard deviation})$. Feed quality was constant throughout the simulation and was based on published experiments (grass: FV=0.95 FU, UFL=1.00, PDI=103; Concentrate UFL=1.10, PDI=126, silage: FV=1.13, UFL=0.75, PDI=51) (McCarthy *et al.*, 2012) and it was assumed that the cows were grazing for their whole lactation.

Model external evaluation

The model was used to simulate two very different experiments, one in Ireland and one in France. Outputs from the model in relation to milk production and BCS were evaluated relative to the experimental data. The next section describes the two

studies used to complete the evaluation. The description of the experiments has been confined to the part relevant to this evaluation.

On farm studies, Irish experimental study 1 (Curtins experiment). The first experimental study has been carried out at the Animal and Grassland Research and Innovation centre, Teagasc, Moorepark, Ireland (52.17°N; -8.27°W). This experiment has been previously fully described in McCarthy *et al.* (2013). Two different SR's have been used to evaluate the model: 3.28 cow/ha (**SR1**) and 2.51 cow/ha (**SR2**). The cows used in this experiment were based on Holstein Friesian of both North American and New Zealand origin balanced for overall genetic merit. Concentrate supplementation was similar for all treatments which started at 4 kg per day post calving and was reduced and removed totally only when herbage supply exceeded animal demand for all treatments (usually mid-March). Cows were milked twice a day and milk yields were recorded individually. Milk fat and protein concentrations were determined weekly from successive evening and morning milkings. Body condition score was assessed every three weeks by the same individual throughout the study on a scale of one to five in increments of 0.25. On the first of January 2009 each SR group were composed of 31 cows and 15 pregnant heifers. The qualities of the grass and concentrate from this experiment are presented in Table 1.

Table 1 around here

On farm studies, French experimental study 2 (LePin experiment). The objective of this experiment carried out at the INRA experimental farm of Le Pin-au-Haras (48.448°N, 0.098°E) was to evaluate over an extended period of time the ability of different breeds of dairy cows to produce and to reproduce under two feeding

strategies in the context of group calving. This experiment has previously been fully described in Cutullic *et al.* (2011). Since 2006, two groups of dairy cows from the Holstein and the Normande breeds were evaluated under two feeding strategies. In early lactation during the winter period (90 days), animals of the high feeding group received an *ab libitum* total mixed ration (TMR) with maize silage (55%), dehydrated alfalfa (15%) (average forage quality 0.90 FV, 0.89 UFL and 76 PDI) and 30% of concentrate (average concentrate quality 1.1 UFL and 165 PDI per kg DM). During the same period animals of the low feeding group were fed *ad libitum* with a TMR composed of grass silage (50%) and haylage (50%) without any concentrate (average of 1.07 FV, 0.92 UFL and 83 PDI). In early April when at grazing, the high feeding group of cows had access to a limited grass area of 0.35 ha per cow (permitting around 90 days of full grazing without forage supplementation) with a grass quality average of 0.98 FV, 0.91 UFL and 100 PDI. They received 4 kg of concentrate per day (average of 1.11 UFL and 136 PDI) and as soon as a grass deficit was detected, 5 to 8 kg of maize silage was added to the diet. The low feeding group of cows had access to a larger grass area of 0.55 ha per cow (permitting 180 days of exclusive grazing) with a grass quality average of 0.97 FV, 0.89 UFL and 102 PDI. They received no concentrate supplementation. Late in autumn, the grazed grass was replaced by grass silage (quality of 1.06 FV, 0.98 UFL and 67 PDI).

Model evaluation. In order to make consistent comparisons, the milk produced in the experiments was transformed into standard milk (Supplementary Equation S12). For the milk production and body condition score, in both experiments, the model was evaluated on a weekly time step.

The maximum theoretical milk yield for the Irish study was set for all mature cows at a mean of 37 kg, (SD: 5 kg) of milk per day. This potential was determined by evaluating the performance of the average actual cows through the 3 years. The average milk yield of the cattle was adjusted to parity 3 equivalents by assuming that parity 1 and parity 2 yield were 75 % and 92 % of parity 3 yields (Hutchinson *et al.*, 2013). As the SRs were balanced for milk yield, the same theoMYmax yield has been applied across SR. Then the level of feeding effect has been included in the calculations as low (SR2) and very low (SR1) leading to a correction of the potential of 1.25 and 1.40 respectively compared to the actual milk deliveries. These corrections were generated based on historical information. For the French study, a specific genetic index (Delaby *et al.*, 2010b) developed for this study was used to generate the individual theoMYmax (average of 53 kg, SD of 5 for the Holstein mature cows, average of 40 kg, SD of 4 for the Normande mature cows). The genetic index included the sire and grandsire's genetic evaluation, the dam's milk production over 3 lactations adjusted for the fixed environmental effect and the feeding treatment applied during each lactation. For the Irish data the prediction of the model was evaluated by comparing average weekly model outputs of the sub-cattle versus the experimental data from the first to the 40th weeks of lactation. The simulation was run for both SR's, and results of multiparous and primiparous cows were evaluated separately.

Using the French data the model prediction of the two different breeds and two different feeding levels was completed by comparing average weekly model outputs of the groups versus the experimental data from the first to 44th week of lactation. Based on individual genetic information available for the French data, it was possible to complete individual animal simulations (as it was possible to estimate the

theoMYmax) and subsequent evaluation. The comparison between the simulation and actual data included the individual weekly average milk yield as well as the BCS for the 3 years. The accuracy of the simulation was evaluated per week and on a seasonal basis spring (early lactation - week 1 to 15), summer (mid lactation - week 16 to 25) and autumn (late lactation - week > 25).

Statistical analyses. The RMSE, RPE and CCC were used to evaluate accuracy of the model when compared to the actual data. The RMSE provides information on the accuracy of the simulation by comparing term by term the actual and predicted data (Bibby and Toutenburg, 1977). The lower the RMSE is, the more accurate the simulation. The RPE is an expression of the RMSE as a percentage of the actual data. According to Fuentes-Pila *et al.* (1996), a RPE lower than 10% indicates a satisfactory prediction, between 10% and 20% a relatively acceptable prediction, and an RPE greater than 20% suggests a poor model prediction. In this study, the RMSE and RPE were used on the comparison of the different sub cattle at the lactation week scale.

The CCC (Lin, 1989, Nickerson, 1997) evaluates the correlation between two datasets but also the deviation from the 45° line. The strength of agreement is considered as poor if the CCC is lower than 0.65, moderate if between 0.65 and 0.80, substantial if between 0.80 and 0.90 and almost perfect if greater than 0.90 (McBride, 2005).

Results

Sensitivity analyses

The results of the sensitivity analyses in terms of milk yield and BCS are presented in Figure 2 and 3. In the simulations, the average daily milk production was 26.4 kg per cow across all simulations (HA, concentrate and theoMYmax). The highest average simulated milk yield corresponded to 33.3 kg per cow under the 50 theoMYmax, HA of 22 kg/cow and 4 kg of concentrate with the lowest average milk yield simulated corresponding to 20.1 kg for the 30 theoMYmax, HA of 14, without concentrate supplementation. An increase of 1 kg of theoMYmax resulted in an average increase of 0.4 kg of milk produced. An increase of 1 kg of HA resulted in an average increase of 0.2 kg of milk per cow per day (minimum of 0.1, maximum of 0.5) which was higher for the 50 theoMYmax cow (average of 0.3 kg) than for the 30 theoMYmax (average of 0.1 kg). An increase of 1 kg concentrate resulted in an average increase of 0.8 kg of milk per cow per day (maximum of 1.1 kg minimum of 0.5 kg) with this increase being higher for the 50 theoMYmax cow (average of 0.9 kg) than for the 30 theoMYmax (average of 0.6 kg). Furthermore this increase was higher at an HA of 14 (average of 0.9 kg) than at an HA of 22 (average of 0.6 kg).

Figure 2 and 3 around here

The average BCS loss was of 0.63 units between calving and nadir, with a maximum loss of 1.1 for the 50 theoMYmax, HA 14 kg with no concentrate and a minimal loss of 0.2 units for the 30 theoMYmax, HA 22, 4 kg of concentrate. The impact of an increase of 1 kg in theoMYmax resulted in an average increase in BCS loss of 0.03 units of BCS to the nadir. The impact of an increase of 1 kg of HA resulted in an average decrease of 0.01 units of BCS loss to the nadir. In terms of concentrate the increase of 1 kg of concentrate resulted in an average decrease of BCS loss of 0.05 units.

433

434 *Curtins experiment*

435 *Model outputs.* The model simulated a higher daily (1.3 kg of milk per cow) and
436 annual (893 kg of milk per cow) milk production for the multiparous cows managed
437 under the SR2 treatment than under the SR1 (Table 2). The same trend was
438 observed for the primiparous cows with an average increase of daily production of
439 1.8 kg per cow and an average increase of 907 kg of milk through the whole lactation
440 from the SR1 to the SR2 treatment. For the BCS the model simulated a higher
441 average BCS throughout lactation for the SR2 than for the SR1 (0.15 units higher for
442 the multiparous and 0.05 higher for the primiparous) (Table 2). The model simulated
443 a higher average BCS for the primiparous cows than for the multiparous cows
444 (average of 3.03 against 2.87). The BCS loss across the different stocking rates was
445 similar with 0.47 and 0.44 for the SR1 and SR2 respectively (average between
446 primiparous and multiparous).

447 *Table 2 around here*

448

449 *Model evaluation.* Over the total lactation, the weekly milk production for the SR1
450 group of cows had an RPE of 6.97% for the multiparous cows and 11.86% for the
451 primiparous cows (Table 2) when the model outputs and the experimental data were
452 compared. The higher RPE for the primiparous cows was related to an
453 underestimation of the milk production of these group of cows in the spring
454 (RPE=13% and RMSE=2.58 kg) and a slight underestimation of the milk production
455 in autumn (RPE=10% and RMSE=1.32 kg). For both primiparous and multiparous
456 cows in SR1, the BCS through lactation and per season resulted in an RPE which
457 was lower than 4% and the RMSE lower than 0.10 units of BCS (Table 2). The

weekly milk production of the SR2 group of cows was reasonable with the RPE throughout lactation and at a seasonal level lower than 8% for both multiparous and primiparous SR2 cows (Table 2). On the cumulative milk yield the primiparous SR2 cows had a RPE of 2% and RMSE of 115 kg of milk. For the multiparous cows, the model overestimated the milk yield with an RPE of 11% and a RMSE of 680 kg. The difference in percentage of error between the weekly milk yield and the cumulative milk yield is due to the difference in the lactation length between actual and predicted. The BCS of the SR2 animals resulted in an RPE which was less than 5% with the RMSE lower than 0.15 units (Table 2).

The accuracy of the model was similar for both SR's, however there was a decrease in precision in the model for the primiparous cows in the SR1 groups.

Le Pin experiment

Model output. The model simulated a higher average milk production for the high feeding group (average of 25.7 kg of milk per cow per day) of cows than for the low feeding group of cows (average of 20.3 kg of milk) and a higher milk production for the Holstein cows (average of 24.7 kg of milk) over the Normande cows (average of 21.3 kg of milk) (Table 3). On average through the overall lactation the high feeding group of cows produced 1 935 and 1 486 kg per cow more milk than the low feeding group for the Holstein and the Normande groups of cows, respectively (Table 3). The model simulated a higher BCS loss for the Holstein than for the Normande (average of 0.89 against 0.64) group and a slightly higher loss for the low feeding group than for the high feeding group (average of 0.85 against 0.68).

Table 3 around here.

483 *Model evaluation.* For the high feeding group, the weekly milk production had an
484 RPE which was less than 10% at both overall lactation and seasonal scale for both
485 Holstein and Normande cows (Table 3). For the average BCS the model had an
486 RPE which was less than 10% with all computed RMSE figures lower than 0.25 units
487 for the high feeding group of cows (Table 3). The differences between the actual and
488 the predicted BCS loss were 0.06 for the Holstein and 0.14 for the Normande cows.
489 For the cows in the low feeding systems when compared on a weekly basis, all RPE
490 values were less than 15% for milk yield (Table 3). The model has a tendency to
491 slightly overestimate the milk production for both Holstein and Normande cows in the
492 low feeding systems in summer (RPE of 14% and 11%, RMSE of 2.73 kg/cow per
493 day and 1.95 kg/cow per day respectively) and autumn (RPE of 14% and 12%,
494 RMSE of 2.35 kg/cow per day and 1.74 kg/cow per day). For the average BCS the
495 prediction were relatively accurate with all RPE values less than 15% and all RMSE
496 values less than 0.25 units except for the low feeding Holsteins in autumn (RMSE of
497 0.27) (Table 3). The differences between the actual and predicted BCS loss are 0.02
498 for the Holstein and 0.16 for the Normande groups.
499 The model has been more accurate in simulating the high feeding levels than the low
500 in terms of milk production due to an over prediction of the milk production of the low
501 feeding group in autumn. In terms of BCS the model was slightly more accurate in
502 predicting the BCS of the Holstein than the Normande cows due to an
503 underestimation of the BCS of the Normande group.
504 As the genetics of the individual cows was available, a comparison at individual cow
505 level was also completed for both breed and feeding systems together. For the total
506 milk production throughout lactation the CCC was 0.85 with a coefficient of bias of

0.97 (Figure 4). On the comparison by week of lactation the CCC was 0.84 with a coefficient of bias of 0.99.

Figure 4 around here

Discussion

Overall assessment of the model

The model developed in this study has been able to react in a sensible fashion to variation in concentrate feed levels, herbage allowance and herd genetic potential. Using the French data, the model was capable of reproducing the impact of the different types of feeding (high and low feeding group) as well as the different types of feeding intra group (TMR, grazing and indoor feeding). The model was also capable of reproducing the higher milk production and BCS loss of the Holstein cows when compared to the Normande cows. For the Irish data, the model was capable of adapting to the two different stocking rates by simulating higher average milk yields per cow for the lower stocking rates showing the ability of the model to react realistically to variation in feed levels. Primiparous cows have also produced significantly less milk than the multiparous cows in the simulation.

In relation to herbage allowance and concentrate feed level variation, the model responses are within the range of previously published studies. In this model the impact of theoretical milk is higher in early lactation (between 4.2 to 6.0 kg of standard milk per 10 kg of theoretical milk) than in late lactation (between 3.0 to 3.9 kg of standard milk). This finding is in agreement with the findings of Buckley *et al.* (2000) which showed that a higher peak milk yield is associated with a steeper decline (less persistent) lactation curves, which leads to a decrease of the impact of

genetic potential in late lactation. The outputs from the model show an overall trend that is similar to previous studies with a change from 0.08 to 0.45 kg of milk per kilogram of HA simulated in the model. This compares to 0.02 to 0.23 kg of milk per kg of herbage allowance in the literature. As shown in previous studies, the concentrate response increased with the theoretical milk production (Fulkerson *et al.*, 2008) and it decreased with increasing HA (McEvoy *et al.*, 2008). The outcomes from this model are within the range of the previously published studies for concentrate supplementation (Supplementary Table S5) with the impact of 1 kg of concentrate resulting in an increase of 0.5 to 1.1 kg of standard milk across different genotypes and HA categories. The impact of concentrate supplementation on body condition score loss has been demonstrated by the model. The impact of the increase of 4 kg of concentrate per cow per day resulted in a reduction in the body condition loss post calving, this impact is higher for the LG and MG (0.21 units) than for the HG cow (0.16 units). The model outputs are within the range of previously published studies with a reduction of BCS loss of between 0.03 and 0.05 of BCS per kg of concentrate (Horan *et al.*, 2005, McCarthy *et al.*, 2007).

External evaluation

With an RPE lower than 15% the model can be said to have good accuracies at predicting BCS and milk production (Fuentes-Pila *et al.*, 1996) and is in the range of previous studies. At the herd level, Baudracco *et al.* (2013) presented a model with an RPE of 8.8% for annual milk yield. When compared against 206 experiments, the GrazIN model had an average RPE of 14% at the herd level (Delagarde *et al.*, 2011b). Primiparous cows in the GrazIN model had a higher RPE (19%) than for multiparous cow (11%) (Faverdin *et al.*, 2011). At individual animal level Baudracco *et al.* (2013) predicted the milk yield with a CCC 0.74 and 0.77 with observed milk

yields for two different cow breeds. When taking all of these components together, this model can be said to be as least as good or better across a range of different evaluation criteria.

For the Irish data, the model developed in this study had a satisfactory prediction for milk yield on the overall lactation for both stocking rates. However there were some points of discrepancy. The underestimation of the model in early lactation of the primiparous SR1 cows shows that the model underestimates the ability of the primiparous cows to compensate for the lack of feed despite a relatively accurate prediction of the BCS. The prediction of BCS change is very accurate for the Irish data with all RPE lower than 5% at the lactation or season levels. Within the French data all RPE were lower than 15% for daily milk production over the lactation which shows that the model is well able to adapt to the different types of feeding (TMR, grazing, indoor feeding). The model had a tendency to slightly overestimate the milk production for the Normande dairy cows in early lactation probably due to the over mobilisation of BCS by the simulated Normande group compared to the actual cows. For both experiments the model predicted the BCS loss and the nadir with precision lower than 0.25 which shows a very good accuracy.

With respect to fitting individual cow data, the CCC of 0.84 with a coefficient of bias of 0.99 for weekly milk production and 0.85 with a coefficient of bias of 0.97 for annual total milk yield, for individual French cows shows that the model is well able to predict at animal level the impact of feeding and individual animal genetics on individual milk yields. However, a good and precise definition of the theoretical milk yield of the cow is needed for accurate simulations. This highlights the need to develop tools for estimating $theoMY_{max}$ in the field to allow for a precise simulation in the model as the results are sensitive to both theoretical maximum milk and BCS

at calving. Finding an accurate theoretical maximum milk yield for the dairy cow is always a challenge as the cows are almost never fed enough to express their full potential (Faverdin *et al.*, 2010) When the model will be ready for commercial farms use, a feature will be added to permit the calculation of the theoMYmax using genetic information and historical information.

Model advancement and limitations

The HDM model is an individual-based model focusing principally on the impact of diet and management on milk production and BCS at individual animal and herd level. Many models have been developed to simulate the production of cattle at grazing but there are varying levels of accuracy and many do not permit the modelling of individual existing animal performance. For example, in the model e-Dairy (Baudracco *et al.*, 2013), which is an individual-based model, each cow is generated randomly at the start of the simulation (for the potential milk yield and the body weight at calving). Contrary to the HDM model, the duration of the simulation is fixed at one year, not allowing the testing of longer term strategies. As in the HDM model the individual and herd milk production, BCS and BW are simulated daily but in addition the daily protein and fat content is also simulated in the e-Dairy model. Models like the one described by Rotz *et al.* (1999) use groups of animals (early mid and late lactation sub divided with multiparous and primiparous cows) to simulate the milk production and BW. Each group has a potential milk yield, a milk fat content, BW, change in BW and a fibre digestive capacity. Once again contrary to the HDM, simulation of a specific animal is not possible neither is the individual simulation of different management regimes of the cow by her genetic potential. A limitation of the model is the use of the theoMYmax. The determination of theoMYmax at the farm

level is challenging. Research is on-going to link the genetics of the animal to this
theoMYmax to permit an accurate use of the model on farm.

The strength of the current model is its ability to balance energy partition between
milk and body reserves according to the gap between intake and requirement.
According to (Martin and Sauvant, 2010b) this allows the model to simulate across a
wide range of genotypes and environments. The model can be defined as efficient in
recreating different extensive grazing scenarios with different animal genetics.
However, further evaluation would be needed if the model would be used for high
genetic merit cows in terms of milk production or very intensive systems with high
levels of concentrate supplementation. The HDM model can be used as the animal
core of a farm systems model (Ruelle *et al.*, 2015) for both research and extension.
This model combined with the system model (the Pasture Based Herd Dynamic
Model) (Ruelle *et al.*, 2015) will be adapted as an online tool to facilitate its use by
farmers and advisors in the future. From a farmer's perspective the combined model
will be used to support the decision making process regarding SR, preGH, postGH
and concentrate supplementation. However, the HDM model only simulates a cow in
what could be described as good health status and does not take into account the
possible impact of mastitis, lameness or other health related events, which would
require further development.

Conclusion

The model presented is capable of adapting to different management systems and
animal breeds in a realistic manner when compared to already published
experiments and experimental data with all RPE lower than 15% for both BCS and
milk production. The model simulates milk production and BCS of the Holstein dairy

cows at grazing as well as in indoor feeding situations accurately. The model is well able to simulate the effects of stocking rate in grass based systems for both multiparous and primiparous cows. However, there is a requirement for more work in relation to body condition score for the Normande breed.

Acknowledgements

The authors would like to acknowledge the personnel of both research farms for the acquisition of the experimental data. Especially Ségolène Leurent-Colette, Adèle Lemerrier and Loic Leloup from the French experimental farm data; Brendan Horan, Brian McCarthy and Adian Brennan for the Irish experimental farm data. The author would like to thank Nicolas Friggens for his help in the preparation of this manuscript. The authors acknowledge the financial support of the FP7 GreenHouseMilk Marie Curie project, SAC for co-hosting and funding from the Research Stimulus Fund 2011 administered by the Department of Agriculture, Fisheries and Food (Project 11/S/132).

References

- Baudracco J, Lopez-Villalobos N, Holmes CW, Comeron EA, Macdonald KA and Barry TN 2013. e-Dairy: a dynamic and stochastic whole-farm model that predicts biophysical and economic performance of grazing dairy systems. *animal* 7, 870-878.
- Baudracco J, Lopez-Villalobos N, Holmes CW, Comeron EA, Macdonald KA, Barry TN and Friggens NC 2012. e-Cow: an animal model that predicts herbage intake, milk yield and live weight change in dairy cows grazing temperate pastures, with and without supplementary feeding. *animal* 6, 980-993.
- Bazin S, Augeard P, Carteau M, Champion H, Chilliard Y, Disenhaus C, Durand G, Espinasse R, Gascoin A, Godineau M, Jouanne D, Ollivier O and Remond B 1984.

659 Grille de notation de l'etat d'engraissement des vaches pie noires. RNED bovin,
660 Paris, France.

661 Bibby J and Toutenburg H 1977. Prediction and improved estimation in linear models. Wiley,
662 New York, United States.

663 Bruce JM, Broadbent PJ and Topps JH 1984. A model of the energy system of lactating and
664 pregnant cows. *Animal Science* 38, 351-362.

665 Buckley F, Dillon P, Rath M and Veerkamp RF 2000. The Relationship Between Genetic
666 Merit for Yield and Live Weight, Condition Score, and Energy Balance of Spring
667 Calving Holstein Friesian Dairy Cows on Grass Based Systems of Milk Production.
668 *Journal of dairy science* 83, 1878-1886.

669 Buckley F, O'Sullivan K, Mee JF, Evans RD and Dillon P 2003. Relationships Among Milk
670 Yield, Body Condition, Cow Weight, and Reproduction in Spring-Calved Holstein-
671 Friesians. *Journal of dairy science* 86, 2308-2319.

672 Cutullic E, Delaby L, Gallard Y and Disenhaus C 2011. Dairy cows' reproductive response to
673 feeding level differs according to the reproductive stage and the breed. *animal* 5,
674 731-740.

675 Delaby L, Peyraud J-L, Foucher N and Michel G 2003. The effect of two contrasting grazing
676 managements and level of concentrate supplementation on the performance of
677 grazing dairy cows. *Animal Research* 52, 437-460.

678 Delaby L, Leurent S, Gallard Y and Schmitt T 2010a. Effet de la race, de la parité, du
679 potentiel laitier et de l'état au vêlage sur l'évolution de l'état corporel des vaches
680 laitières au cours de la lactation In 17èmes Rencontres Recherches Ruminants,
681 Paris, France. doi : http://www.journees3r.fr/IMG/pdf/2010_08_13_Delaby.pdf

682 Delaby L, Faverdin P, Michel G, Disenhaus C and Peyraud J 2009. Effect of different feeding
683 strategies on lactation performance of Holstein and Normande dairy cows. *animal* 3,
684 891-905.

685 Delaby L, Horan B, O'Donovan MA, Gallard Y and Peyraud JL 2010b. Are high genetic merit
686 dairy cows compatible with low input grazing systems? In General Meeting of the

687 European Grassland Federation, Kiel, DEU, pp. 928-930. Doi:
688 http://www.europeangrassland.org/fileadmin/media/EGF2010_GSE_vol15.pdf

689 Delagarde R, Faverdin P, Baratte C and Peyraud JL 2011a. GrazIn: a model of herbage
690 intake and milk production for grazing dairy cows. 2. Prediction of intake under
691 rotational and continuously stocked grazing management. Grass and Forage Science
692 66, 45-60.

693 Delagarde R, Valk H, Mayne CS, Rook AJ, González-Rodríguez A, Baratte C, Faverdin P
694 and Peyraud JL 2011b. GrazIn: a model of herbage intake and milk production for
695 grazing dairy cows. 3. Simulations and external validation of the model. Grass and
696 Forage Science 66, 61-77.

697 Faverdin P, Delagarde R, Delaby L and Meschy F 2010. Alimentation des vaches laitières.
698 In Alimentation des bovins, ovins et caprins, pp. 23-58. Quae, Versailles Cedex,
699 France.

700 .

701 Faverdin P, Baratte C, Delagarde R and Peyraud JL 2011. GrazIn: a model of herbage
702 intake and milk production for grazing dairy cows. 1. Prediction of intake capacity,
703 voluntary intake and milk production during lactation. Grass and Forage Science 66,
704 29-44.

705 Friggens NC, Ingvarlsen KL and Emmans GC 2004. Prediction of Body Lipid Change in
706 Pregnancy and Lactation. Journal of dairy science 87, 988-1000.

707 Fuentes-Pila J, DeLorenzo MA, Beede DK, Staples CR and Holter JB 1996. Evaluation of
708 Equations Based on Animal Factors to Predict Intake of Lactating Holstein Cows.
709 Journal of dairy science 79, 1562-1571.

710 Fulkerson WJ, Davison TM, Garcia SC, Hough G, Goddard ME, Dobos R and Blockey M
711 2008. Holstein-Friesian Dairy Cows Under a Predominantly Grazing System:
712 Interaction Between Genotype and Environment. Journal of dairy science 91, 826-
713 839.

714 Geweke J 1991. Efficient simulation from the multivariate normal and student-t distributions
715 subject to linear constraints and the evaluation of constraint probabilities. In
716 Proceeding of the 23rd Computing science and statistics, 22-24 April, Seattle, United
717 States, pp. 571-578.

718 Hoden A, Peyraud J, Muller A, Delaby L, Faverdin P, Peccatte J and Fargetton M 1991.
719 Simplified rotational grazing management of dairy cows: effects of rates of stocking
720 and concentrate. *Journal of Agricultural Science, Cambridge* 116, 417-428.

721 Horan B, Mee JF, Rath M, O'Connor P and Dillon P 2004. The effect of strain of Holstein-
722 Friesian cow and feeding system on reproductive performance in seasonal-calving
723 milk production systems. *Animal Science* 79, 453-467.

724 Horan B, Dillon P, Faverdin P, Delaby L, Buckley F and Rath M 2005. The Interaction of
725 Strain of Holstein-Friesian Cows and Pasture-Based Feed Systems on Milk Yield,
726 Body Weight, and Body Condition Score. *Journal of dairy science* 88, 1231-1243.

727 Hutchinson I, Shalloo L and Butler S 2013. Expanding the dairy herd in pasture-based
728 systems: The role of sexed semen use in virgin heifers and lactating cows. *Journal of*
729 *dairy science* 96, 6742-6752.

730 INRA 2010. Alimentation des bovins, ovins et caprins. Quae, Versailles Cedex, France.

731 Jacquot A-L 2012. Dynamilk : un simulateur pour étudier les compromis entre performances
732 animales, utilisation des ressources herbagères et recherche d'autonomie
733 alimentaire dans les systèmes bovins laitiers de montagne. *Agricultural science*,
734 Blaise Pascal University, Clermont-Ferrand II, France.

735 Jouven M, Agabriel J and Baumont R 2008. A model predicting the seasonal dynamics of
736 intake and production for suckler cows and their calves fed indoors or at pasture.
737 *Animal Feed Science and Technology* 143, 256-279.

738 Lin LIK 1989. A Concordance Correlation Coefficient to Evaluate Reproducibility. *Biometrics*
739 45, 255-268.

740 Martin O and Sauvant D 2010a. A teleonomic model describing performance (body, milk and
741 intake) during growth and over repeated reproductive cycles throughout the lifespan

742 of dairy cattle. 1. Trajectories of life function priorities and genetic scaling. *animal* 4,
743 2030-2047.

744 Martin O and Sauvant D 2010b. A teleonomic model describing performance (body, milk and
745 intake) during growth and over repeated reproductive cycles throughout the lifespan
746 of dairy cattle. 2. Voluntary intake and energy partitioning. *animal* 4, 2048-2056.

747 Masselin S, Sauvant D, Chapoutot P and Milan D 1987. Les modèles d'ajustement des
748 courbes de lactation. *Annales de zootechnie*, 36, 171-206. doi: [https://hal.archives-](https://hal.archives-ouvertes.fr/hal-00888528/document)
749 [ouvertes.fr/hal-00888528/document](https://hal.archives-ouvertes.fr/hal-00888528/document)

750 McBride GB 2005. A proposal for strength-of-agreement criteria for Lin.s.concordance
751 correlation coefficient. NIWA Client Report: HAM2005-062.

752 McCarthy B, Pierce KM, Delaby L, Brennan A and Horan B 2012. The effect of stocking rate
753 and calving date on reproductive performance, body state, and metabolic and health
754 parameters of Holstein-Friesian dairy cows. *Journal of dairy science* 95, 1337-1348.

755 McCarthy B, Delaby L, Pierce KM, Brennan A and Horan B 2013. The effect of stocking rate
756 and calving date on milk production of Holstein–Friesian dairy cows. *Livestock*
757 *Science* 153, 123-134.

758 McCarthy S, Berry DP, Dillon P, Rath M and Horan B 2007. Influence of Holstein-Friesian
759 Strain and Feed System on Body Weight and Body Condition Score Lactation
760 Profiles. *Journal of dairy science* 90, 1859-1869.

761 McEvoy M, Kennedy E, Murphy JP, Boland TM, Delaby L and O'Donovan M 2008. The
762 Effect of Herbage Allowance and Concentrate Supplementation on Milk Production
763 Performance and Dry Matter Intake of Spring-Calving Dairy Cows in Early Lactation.
764 *Journal of dairy science* 91, 1258-1269.

765 Nickerson CAE 1997. A Note On "A Concordance Correlation Coefficient to Evaluate
766 Reproducibility". *Biometrics* 53, 1503-1507.

767 Rotz CA, Mertens DR, Buckmaster DR, Allen MS and Harrison JH 1999. A Dairy Herd Model
768 for Use in Whole Farm Simulations. *Journal of dairy science* 82, 2826-2840.

769 Ruelle E, Shalloo L, Wallace M and Delaby L 2015. Development and evaluation of the
770 pasture-based herd dynamic milk (PBHDM) model for dairy systems. European
771 Journal of Agronomy 71, 106-114.

772 Vérité R and Delaby L 2000. Relation between nutrition, performances and nitrogen
773 excretion in dairy cows. Annales de Zootechnie, 49, 217-230.

774

Table 1 Information about the quality of the feedstuff by season for the 3 years of the simulation for the dairy lactating cow on the Irish experiment

| | FV ¹ | UFL ² | PDI ³ |
|---------------|-----------------|------------------|------------------|
| Spring forage | 0.95 | 1,00 | 103 |
| Summer forage | 0.97 | 0.98 | 99 |
| Autumn forage | 0.98 | 0.95 | 98 |
| Concentrate | - | 1.09 | 103 |

¹Fill Value

²Energetic value: "Unité Fourragère Lait" (UFL). 1 UFL = 1700kcal NEL (net energy for lactation)

³Proteic value: "Intestinal digestible protein"

Table 2 Comparison between the average actual (A) and simulated (S) standard milk production (kg) and BCS (units) of the dairy cattle for the stocking rate 3.28 (SR1) and 2.51 (SR2) for the multiparous (M) and primiparous (P) cow on the Irish experiment

| | Lactation week | SR1 | | | | SR2 | | | |
|---------|------------------|--------|--------|-------------------|----------------------|--------|--------|-------------------|----------------------|
| | | Mean A | Mean S | RMSE ¹ | RPE ² (%) | Mean A | Mean S | RMSE ¹ | RPE ² (%) |
| M I L K | Total milk yield | 5336 | 5916 | 580 | 10.86 | 6129 | 6809 | 680 | 11.10 |
| | 1-40 | 20.7 | 21.4 | 1.4 | 6.97 | 22.5 | 22.7 | 1.5 | 6.64 |
| | 1-16 | 25.5 | 25.6 | 1.7 | 6.57 | 26.9 | 27.5 | 2.0 | 7.50 |
| | 17-25 | 20.2 | 21.8 | 1.6 | 7.94 | 22.5 | 23.3 | 1.1 | 4.80 |
| | 26-40 | 16.0 | 16.8 | 1.0 | 6.11 | 17.9 | 17.4 | 0.9 | 5.10 |
| | Max milk yield | 28.3 | 28.5 | | | 29.9 | 30.4 | | |
| | Total milk yield | 4613 | 4397 | 225 | 4.87 | 5419 | 5304 | 115 | 2.12 |
| | 1-40 | 16.0 | 15.7 | 1.9 | 11.86 | 17.5 | 17.5 | 0.9 | 5.07 |
| | 1-16 | 19.5 | 17.2 | 2.6 | 13.22 | 19.6 | 19.0 | 1.1 | 5.46 |
| | 17-25 | 15.4 | 15.9 | 1.0 | 6.62 | 17.6 | 18.2 | 0.8 | 4.39 |
| B C S | 26-40 | 12.7 | 13.9 | 1.3 | 10.40 | 15.2 | 15.4 | 0.7 | 4.31 |
| | Max milk yield | 21.2 | 19.1 | | | 21.6 | 20.6 | | |
| | 1-40 | 2.82 | 2.79 | 0.07 | 2.36 | 2.97 | 2.94 | 0.12 | 4.12 |
| | 1-16 | 2.86 | 2.81 | 0.06 | 2.16 | 2.99 | 2.91 | 0.10 | 3.34 |
| | 17-25 | 2.72 | 2.69 | 0.06 | 2.11 | 2.95 | 2.82 | 0.14 | 4.69 |
| | 26-40 | 2.82 | 2.84 | 0.07 | 2.33 | 2.97 | 3.04 | 0.12 | 4.03 |
| | nadir | 2.67 | 2.70 | | | 2.92 | 2.78 | | |
| | BCS loss | 0.50 | 0.48 | | | 0.33 | 0.45 | | |
| | 1-40 | 2.95 | 3.00 | 0.07 | 2.54 | 3.05 | 3.05 | 0.06 | 2.03 |
| | 2-16 | 3.08 | 3.08 | 0.03 | 1.13 | 3.14 | 3.12 | 0.05 | 1.50 |
| P | 17-25 | 2.87 | 2.93 | 0.07 | 2.47 | 2.99 | 2.97 | 0.05 | 1.56 |
| | 26-40 | 2.85 | 2.95 | 0.10 | 3.55 | 2.98 | 3.03 | 0.07 | 2.51 |
| | nadir | 2.80 | 2.93 | | | 2.94 | 2.96 | | |
| | BCS loss | 0.63 | 0.45 | | | 0.51 | 0.43 | | |

¹RMSE: root mean square error

²RPE: relative prediction error

Table 3 Comparison between the average actual (A) and simulated (S) standard milk production (kg) and BCS (units) of the dairy cattle for the high and low feeding system for the Holstein (H) and Normande (N) cow on the French experiment

| | Lactation week | High | | | | Low | | | |
|------------------|----------------|--------|--------|-------------------|----------------------|--------|--------|-------------------|----------------------|
| | | Mean A | Mean S | RMSE ¹ | RPE ² (%) | Mean A | Mean S | RMSE ¹ | RPE ² (%) |
| M I L K | Total milk | 8348 | 8359 | 11 | 0.13 | 6170 | 6424 | 254 | 4.11 |
| | 1-44 | 27.3 | 27.8 | 1.6 | 5.81 | 20.2 | 21.6 | 2.1 | 10.58 |
| | 1-16 | 34.2 | 34.7 | 1.8 | 5.24 | 24.8 | 24.5 | 1.3 | 5.32 |
| | 17-25 | 25.9 | 27.8 | 1.9 | 7.48 | 19.9 | 22.6 | 2.7 | 13.75 |
| | 26-44 | 22.2 | 21.9 | 1.2 | 5.19 | 16.4 | 18.6 | 2.4 | 14.38 |
| | Max milk yield | 37.8 | 38.3 | | | 28.8 | 26.8 | | |
| | Total milk | 6776 | 7030 | 254 | 3.37 | 5278 | 5544 | 266 | 5.05 |
| | 1-44 | 22.4 | 23.6 | 1.7 | 7.59 | 17.6 | 18.9 | 1.6 | 8.86 |
| | 1-16 | 27.9 | 29.4 | 2.3 | 8.15 | 21.1 | 21.7 | 1.0 | 4.61 |
| | 17-25 | 22.0 | 24.0 | 2.0 | 9.12 | 18.4 | 20.3 | 2.0 | 10.56 |
| | 26-44 | 18.1 | 18.5 | 0.7 | 3.69 | 14.3 | 16.0 | 1.7 | 12.20 |
| | Max milk yield | 30.1 | 32.7 | | | 22.5 | 23.7 | | |
| B C S | 1-44 | 2.45 | 2.28 | 0.18 | 7.53 | 1.83 | 1.66 | 0.20 | 10.73 |
| | 1-16 | 2.53 | 2.40 | 0.15 | 5.73 | 1.87 | 1.82 | 0.06 | 3.27 |
| | 17-25 | 2.27 | 2.09 | 0.18 | 7.92 | 1.72 | 1.56 | 0.17 | 9.89 |
| | 26-44 | 2.48 | 2.27 | 0.21 | 8.58 | 1.84 | 1.57 | 0.27 | 14.60 |
| | Nadir | 2.23 | 2.08 | | | 1.64 | 1.54 | | |
| | BCS loss | 0.79 | 0.85 | | | 0.90 | 0.92 | | |
| | 1-44 | 3.31 | 3.14 | 0.18 | 5.35 | 2.69 | 2.48 | 0.22 | 8.05 |
| | 1-16 | 3.29 | 3.15 | 0.15 | 4.53 | 2.78 | 2.60 | 0.18 | 6.39 |
| | 17-25 | 3.20 | 2.97 | 0.23 | 7.13 | 2.60 | 2.36 | 0.24 | 9.17 |
| | 26-44 | 3.37 | 3.22 | 0.17 | 5.05 | 2.66 | 2.44 | 0.23 | 8.83 |
| | Nadir | 3.17 | 2.96 | | | 2.58 | 2.35 | | |
| | BCS loss | 0.36 | 0.5 | | | 0.62 | 0.78 | | |

¹RMSE: root mean square error

²RPE: relative prediction error

Figure captions

Figure 1 Flow diagram representing the running of the model to predict the real milk yield of an animal.

Figure 2 Influence of the genetic milk potential of the cow (a: 30kg, b: 40kg, c: 50kg), the herbage allowance per cow (grey dot: 14; black dot: 18, black line: 22) and the amount of concentrate per cow per day (thin line:0, bold line 4) on average standard milk yield (kg) of a dairy herd

Figure 3 Influence of the genetic milk potential of the cow (a: 30kg, b: 40kg, c: 50kg), the herbage allowance per cow (grey dot: 14; black dot: 18, black line: 22) and the amount of concentrate per cow per day (thin line:0, bold line 4) on average body condition score (1-5) of a dairy herd

Figure 4 Comparison between the individual actual and predicted total lactation standard milk yield of the French cows. One dot represents the global milk production of one cow through one lactation. The full dot represent the high feeding level, empty dot the low feeding level, the round dot the Holstein cows and the square dot the Normande cows.

Figure 1

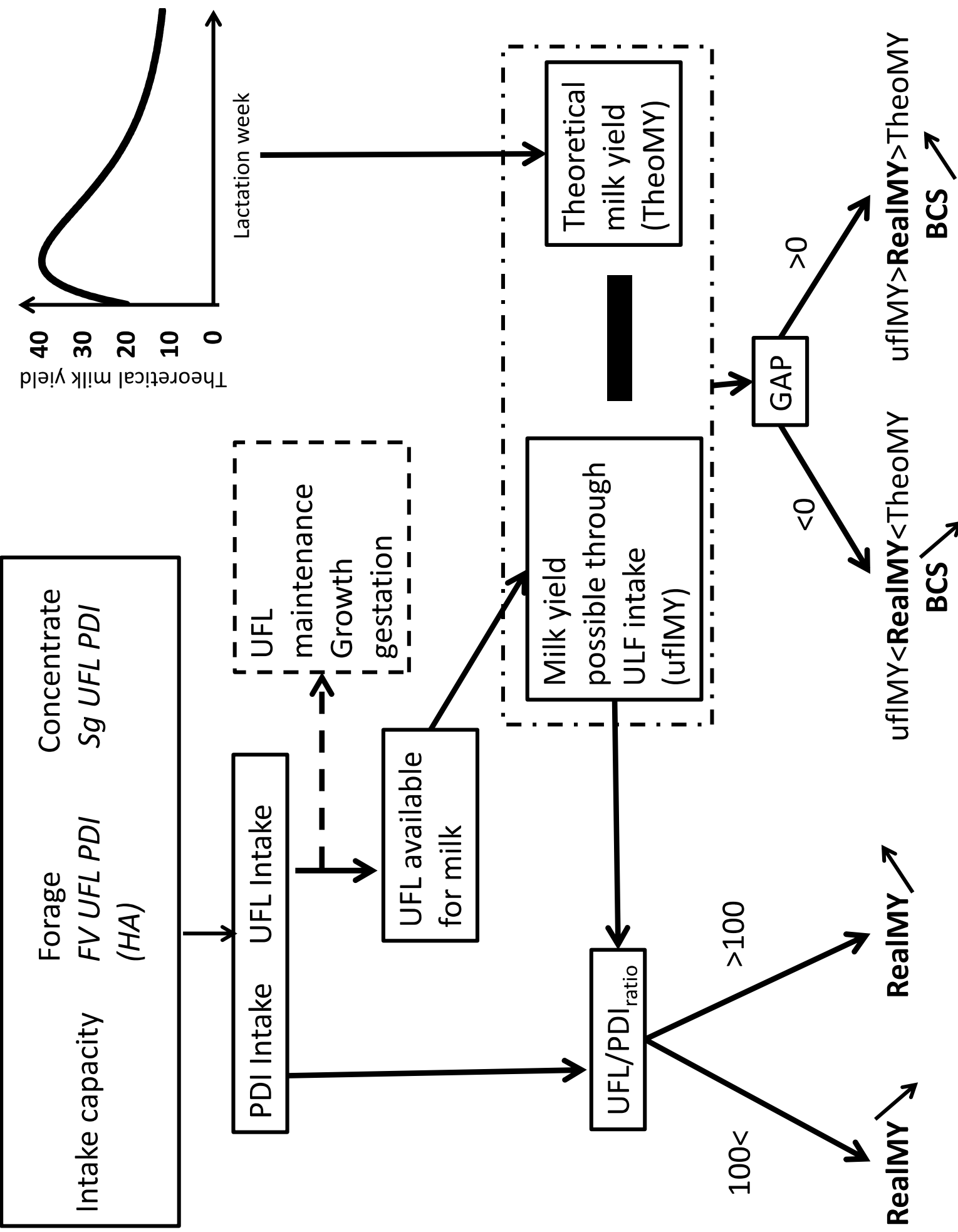


Figure 2

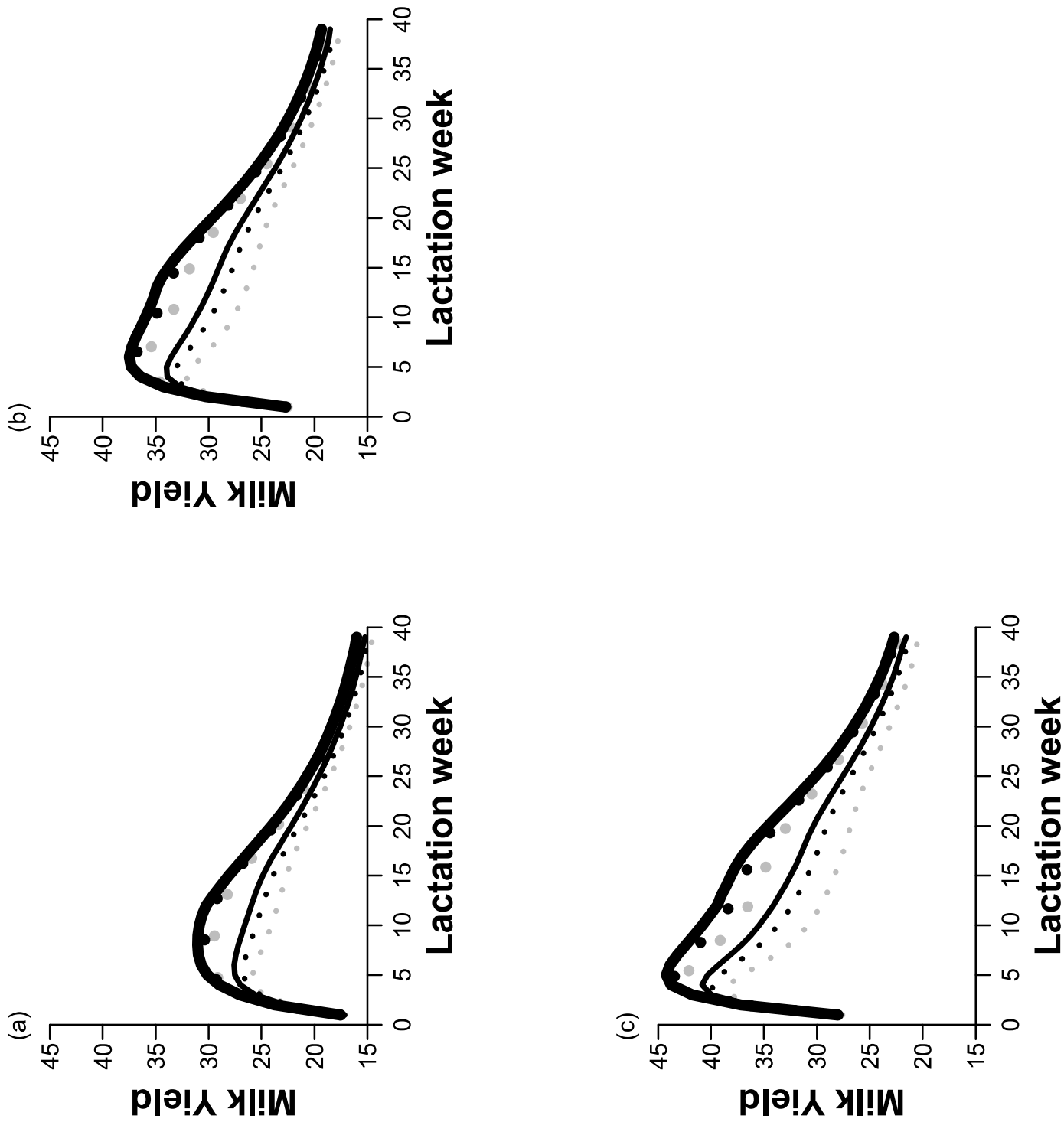
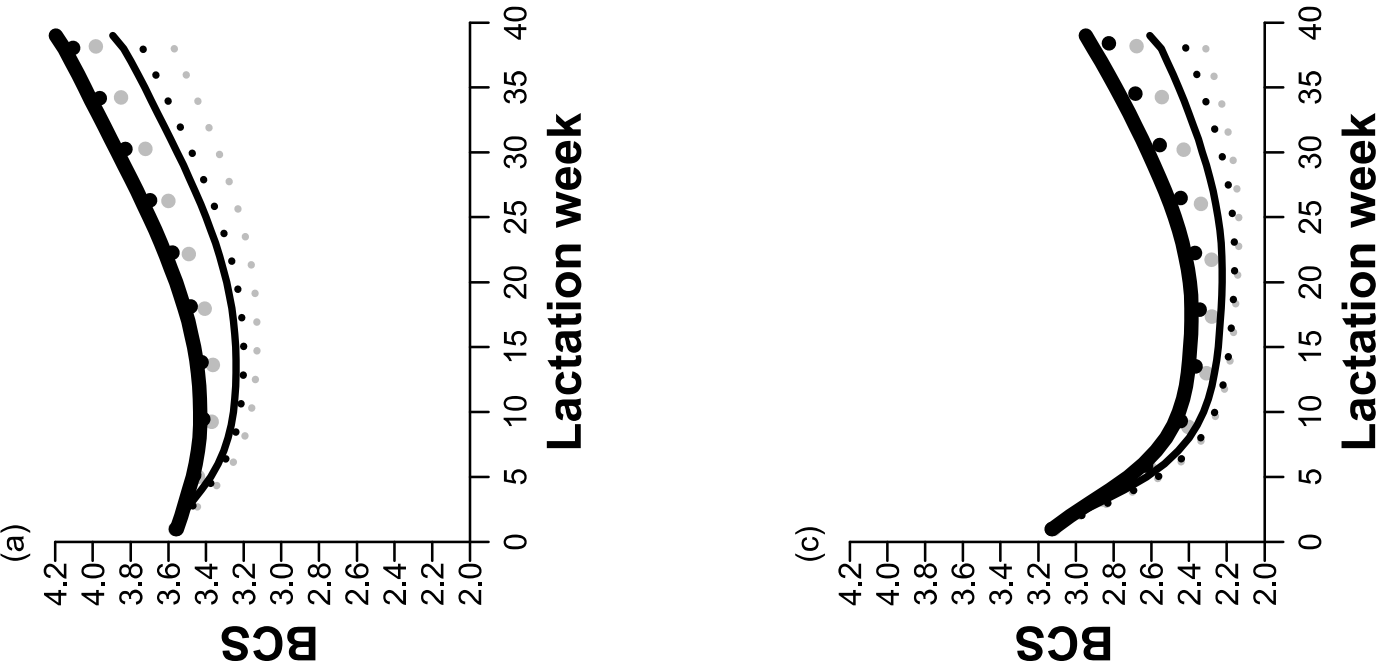


Figure 3



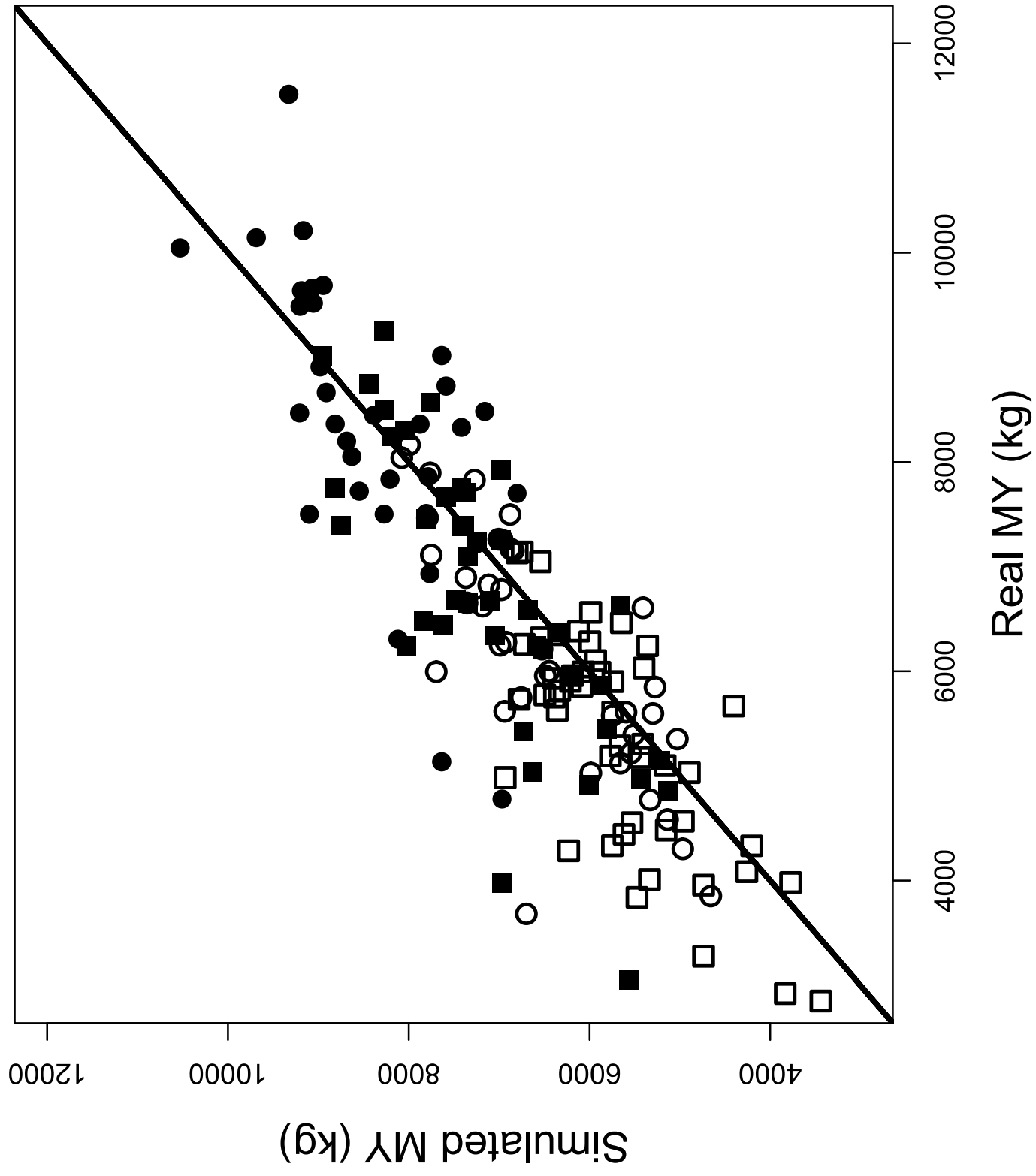


Figure 4

Development and evaluation of the herd dynamic milk (HDM) model with focus on the individual cow component

E. Ruelle^{1,2} L. Delaby³, M. Wallace⁴ and L. Shalloo¹

Supplementary Material S1: Feeding, bcs change and milk production of the dairy cow

The intake and the requirement of the animal is based on the model GrazeIN all the equation and justification are described in (Delagarde *et al.*, 2011a, Delagarde *et al.*, 2011b, Faverdin *et al.*, 2011). The calculation of the intake and intake at grazing is fully describe in (Delagarde *et al.*, 2011a, Faverdin *et al.*, 2011) and won't be re describe here. The only differences are that the MPprot (equation 20 is (Faverdin *et al.*, 2011)) is replaced by the TheoMY (equation X and Y) and that the UFL_mob (equation 19 in (Faverdin *et al.*, 2011)) is replaced by the actual BCSloss of the previous day in the HDM.

Requirement of the animal

Supplementary Equation S1: $UFLreq = GrowthReq + GestReq + MaintReq$

Supplementary Equation S2: $GrowthReq = 3.25 - 0.08 \times Age$

with Age in months,

Supplementary Equation S3: $GestReq = 0.00072 \times BW_{calf} \times e^{0.116 \times \frac{GestD}{7}}$

With BW_{calf} the BW of the calf at birth and GestD the day in gestation of the cow

(Linked with the Gest requirement the BW of the cow increase of GestReq/4.5)

Supplementary Equation S4: $MaintReq = (0.041 \times BW^{0.75}) \times Coeff_req$

with Coeff_req equal to 1.2 at grazing and 1.1 for indoor feeding (Faverdin *et al.*, 2010).

Energetic interaction:

Supplementary Equation S5: $E = 6.3 \times \%C^2 - 0.017 \times UFL_{int} + 0.002 \times UFLing_{int}^2$

with %C the percentage of concentrate in the diet and UFL_{int} the quantity of UFL ingested during the day in UFL.

Grummer *et al.* (1995) has shown that for the first eight weeks of the lactation for a primiparous cow, growth rate is substantially reduced with most of the energy consumed directed toward milk production. Taking this into account, it has been assumed that during the eight first weeks of lactation, the growth of the younger cow

slows down, therefore, there is a requirement for a coefficient to be multiplied to the growth requirement of the animal:

Supplementary Equation S6: $growth_coefficient = \frac{nb_day_in_milk}{7 \times 8}$

with nb_day_in_milk the number of days in milk of the cow, 7 the number of days per week and 8 the eight weeks involved in the reduction of the growth rate.

UFL balance:

Supplementary Equation S7:

$$UFLbalance = 0.3 \times UFLint_{D-2} + 0.7 \times UFLint_{D-1} - (UFL_Req + MY \times 0.44) - E$$

If the cows are dry the UFL balance is calculated with a MY equal to 0, the requirement due to milk is set at 0.

BW and BCS change in case of negative energy balance:

Supplementary Equation S8: $BCSchange = \frac{UFLbalance}{250}$

Supplementary Equation S9: $BWchange = \frac{UFLbalance}{3.5}$

With the BCSchange in unit of BCS.

BW and BCS change in case of positive energy balance:

Supplementary Equation S10: $BCSchange = UFLbalance \times \left(0.0034 - \frac{0.000004}{e^{-1.325 \times BCS}} \right)$

Supplementary Equation S11: $BWchange = \frac{UFLbalance}{4.5}$

For every day, the BCSpool is calculated as the actual BCSpool from previous day minus the BCSchange taking into account an upper bound limit of 0 and a lower bound limit of the theoMOBmax (the theoMOBmax is always negative).

Equation to go from actual milk yield to standard milk yield:

Supplementary Equation S12: (Faverdin *et al.*, 2010)

$$MY = \frac{actualMY \times (0.44 + 0.0055 \times (FC - 40) + 0.0033 \times (PC - 31))}{0.44}$$

with actualMY the non corrected milk yield in kg, FC and PC the fat and protein content in gram per kg of non corrected milk.

Supplementary Material S2: Fertility calculation

Interval between two heat event: $N(22.75, 3.17)$ (Brun-Lafleur, 2011)

Calculation of the return in heat:

$N(47.9 - 5.7 * (2.63 - \text{BCS}_{\text{calv}}), 27.4)$ days after calving (Pryce *et al.*, 2001)

The percentage of foetal death is set at 3% (abortion) (Brun-Lafleur *et al.*, 2013) the rate of late embryonic death is set at 20% (Cutullic *et al.*, 2011).

Supplementary Table 1: Description of the different percentage and coefficient used to calculate the percentage of change of recalving (RC) after artificial insemination (AI) for the dairy cow (taking into account the fact that to be inseminated the farmer need to have seen that the cow was in heat its depending on the heat detection level which is an input)

| | Description | percentage | modification | reference |
|-------------|---|------------|--------------|---|
| First AI RC | Basic percentage for parity 1 to 3 | 44 | | (Inchaisri <i>et al.</i> , 2010) |
| | parity bigger than 3 | 39 | | |
| | parity 2 and 3 inseminate between DIM 40-60 | 39 | | |
| | parity bigger than 3 between DIM 40-60 | 31 | | |
| other AI RC | basic percentage | 42 to 49 | | (Dillon <i>et al.</i> , 2003, Inchaisri <i>et al.</i> , 2010) |
| Overall | occur between DIM 21 and 40 | | x 2/3 | (McDougall <i>et al.</i> , 2012) |
| | occur before DIM 21 | | x 1/2 | |
| | last calving ease of 3 | | x 0.64 | |
| | non Holstein cow | | +10% | |

Supplementary Material S3: Calving calculation:

Percentage of chance to have twin: 1% for parity 1, 3.8% for parity 2, 4.9 for parity 3 and more.

*Supplementary Table S2: Percentage of the different calving ease score depending on cow and calf parameters (Lombard *et al.*, 2007, Mee *et al.*, 2011):*

| | 1 | 2 | 3 |
|-------------|-------|-------|-------|
| Parity 1 | 48.8% | 32.3% | 18.9% |
| Parity 2 | 70.6% | 22.5% | 6.9% |
| Single calf | 65.9% | 23.4% | 10.7% |
| Twin | 44.3% | 44.3% | 12.4% |
| Female calf | 67% | 24.8% | 8.2% |
| Male calf | 60% | 26.5% | 13.4% |

Furthermore, if the previous calving had a calving ease score of 3 the probability of a score of 1 is unchanged the probability of a score of 2 is multiplied by 1.65 the probability of a score of 3 is multiplied by 2.9 (the actual percentage are recalculated after).

Supplementary Material S4: Creation of the new calf

BW of the calf at calving (consider that the BW of the calf at calving will depend on the sum of the gestation requirement during the year with an average calf weight at calving of 42):

$$\text{Supplementary Equation S13: base} = \frac{\sum_{k=0}^{DIG} 0.00072 \times 42 \times e^{0.116 \times \frac{k}{7}}}{4.5}$$

if it's a heifer the base is reduce of 5 kg.

If there is twin the base is reduce of 5.

Finally the BW of the calf at calving will be: $BW = N(\text{base}, 1) - 5$

The BW of the cow is changed in accordance by deleting twice the BW of the calf (only 1.5 if it's twins).

The calf genetic index is calculated as it's mother genetic index multiply by 1.02 plus $N(0, 1)$.

Supplementary Material S5: Death of the animals

The basic percentage of stillbirth is set at 2 (can be changed). This percentage is multiply by 1.7 for a primiparous cow, by 2.3 if the calving ease score is 2, 15.4 if the calving ease score is 3, 2.7 is there is twin, 1.4 if the calf is a male (Lombard *et al.*, 2007).

Supplementary Table S3: Annual probability of death depending on the parity (Miller et al., 2008):

| Parity | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8+ |
|--------------|------|------|------|------|------|------|------|------|
| Base % death | 2.05 | 2.66 | 3.72 | 4.38 | 4.83 | 5.78 | 5.92 | 6.40 |

Supplementary Table S4: Multiplicatif coefficient for the probability of death depending on the month of the year (Miller et al., 2008):

| Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|-------|------|------|------|------|------|------|------|------|------|------|------|------|
| coeff | 1.00 | 1.10 | 1.07 | 0.99 | 0.95 | 0.95 | 1.05 | 1.13 | 1.01 | 0.90 | 0.89 | 0.98 |

Coefficient multiplied by 1.81 if the last calving ease was of 3.

Those coefficients are the annual percentage of death. It is considered that half of the “chances” occur the day of calving.

Supplementary Material S5: Calf and heifer feeding and growing

The hypothesis is made that the calf (0 to 91 days) are growing of 600g per day.

The intake capacity of the heifer (IC) is calculated as (Agabriel and Meschy, 2010):

$$\text{Supplementary Equation S14: } IC = 0.035 * BW^{0.9}$$

Calculation of the actual forage intake (iterative process) for more information/explanation (Agabriel and Meschy, 2010):

$$\text{Supplementary Equation S15: } A = 1 - (1.26 \times (avFVfor - 0.85))^{0.84}$$

With avFVfor the average fill value of the forage intake

$$\text{Supplementary Equation S16: } D = \frac{1}{avFVfor} - A$$

$$\text{Supplementary Equation S17: } B = \frac{avFVfor}{2.04 \times D}$$

$$\text{Supplementary Equation S18: } K = avFVfor \times D \times e^{\frac{B}{0.7}}$$

$$\text{Supplementary Equation S19: } Sg = \frac{0.86}{avFVfor} \times \left(1 - K \times e^{\frac{-B}{1-\%C}}\right)$$

Sg: the concentrate substitution rate

%C percentage of concentrate (between 0-1)

$$\text{Supplementary Equation S20: } forageIntake = \frac{(IC - Qc \times Sg)}{avFVfor}$$

Qc quantity of concentrate

Growth:

$$\text{Supplementary Equation S21: } dailyGrowth = \left(\frac{\frac{UFL_{intake} - GestReq}{BW^{0.75}} - 0.045}{0.0336} \right)^{\frac{1}{1.457}}$$

With UFL intake the ufl intake

With GestReq the UFL requirement for gestation (Supplementary Equation S3).

Supplementary Table S5: Comparison of the impact of the increase of 1kg of concentrates per cow per day in the model to the actual impact shown in published studies on the daily milk production of a dairy cow

| Time of the lactation | Model output (kg of milk/day/cow) | Literature output (kg of milk/day/cow) |
|---|--------------------------------------|--|
| Early lactation (lactation weeks 1-16) | 0.75-1.38 | 0.54-0.88 (McEvoy <i>et al.</i> , 2008) |
| | | 0.51-1.18 (Gill and Kaushal, 2000) |
| | | 0.92-1.08 (Roche <i>et al.</i> , 2007) |
| | | 0.5-1.3 (Kennedy <i>et al.</i> , 2003) |
| | | 0.95-1.35 (Kennedy <i>et al.</i> , 2007) |
| | | 0.50-1.63 (Delaby <i>et al.</i> , 2003) |
| Mid lactation (lactation weeks 17-25) | 0.5-1.45 | 0.7-1.1 (Robaina <i>et al.</i> , 1998) |
| Late lactation (lactation weeks 26-39) | 0.2-0.65 | 0.5-1 (Kennedy <i>et al.</i> , 2003) |
| | | 0.42-1.39 (Delaby <i>et al.</i> , 2001) |
| Whole lactation (lactation weeks 1-39) | 0.5-1.12 | 0.63-1.63 (Fulkerson <i>et al.</i> , 2008) |
| | | 0.76-1.1 (Bargo <i>et al.</i> , 2002) |
| | | 0.39-0.75 (Reis and Combs, 2000) |
| | | 0.33-0.9 (McCarthy <i>et al.</i> , 2007) |
| | | 0.23-1.06 (Roche <i>et al.</i> , 2006) |
| | | 1.18-0.5 (Horan <i>et al.</i> , 2005) |
| | | 0.76-1.09 (Tozer <i>et al.</i> , 2004) |
| | | 0.60-1.57 (Delaby <i>et al.</i> , 2003) |

References

- Agabriel J and Meschy F 2010. Alimentation des veaux et génisses d'élevage. In Alimentation des bovins, ovins et caprins (ed. Quae), pp. 77-89, INRA.
- Bargo F, Muller LD, Delahoy JE and Cassidy TW 2002. Milk Response to Concentrate Supplementation of High Producing Dairy Cows Grazing at Two Pasture Allowances. *Journal of dairy science* 85, 1777-1792.
- Brun-Lafleur L 2011. Modélisation du fonctionnement d'un troupeau laitier pour anticiper les conséquences de son pilotage. Agrocampus-Ouest.
- Brun-Lafleur L, Cutullic E, Faverdin P, Delaby L and Disenhaus C 2013. An individual reproduction model sensitive to milk yield and body condition in Holstein dairy cows. *animal* 25, 1-12.
- Cutullic E, Delaby L, Gallard Y and Disenhaus C 2011. Dairy cows' reproductive response to feeding level differs according to the reproductive stage and the breed. *animal* 5, 731-740.
- Delaby L, Peyraud JL and Delagarde R 2001. Effect of the level of concentrate supplementation, herbage allowance and milk yield at turn-out on the performance of dairy cows in mid lactation at grazing. *Animal science (Penicuik, Scotland)* 73, 171-181.
- Delaby L, Peyraud J-L, Foucher N and Michel G 2003. The effect of two contrasting grazing managements and level of concentrate supplementation on the performance of grazing dairy cows. *Animal Research* 52, 437-460.
- Delagarde R, Faverdin P, Baratte C and Peyraud JL 2011a. Grazeln: a model of herbage intake and milk production for grazing dairy cows. 2. Prediction of intake under rotational and continuously stocked grazing management. *Grass and Forage Science* 66, 45-60.
- Delagarde R, Valk H, Mayne CS, Rook AJ, González-Rodríguez A, Baratte C, Faverdin P and Peyraud JL 2011b. Grazeln: a model of herbage intake and milk production for grazing dairy cows. 3. Simulations and external validation of the model. *Grass and Forage Science* 66, 61-77.
- Dillon P, Snijders S, Buckley F, Harris B, O'Connor P and Mee JF 2003. A comparison of different dairy cow breeds on a seasonal grass-based system of milk production: 2. Reproduction and survival. *Livestock Production Science* 83, 35-42.
- Faverdin P, Delagarde R, Delaby L and Meschy F 2010. Alimentation des vaches laitières. In Alimentation des bovins, ovins et caprins (ed. Quae), pp. 23-58, INRA.
- Faverdin P, Baratte C, Delagarde R and Peyraud JL 2011. Grazeln: a model of herbage intake and milk production for grazing dairy cows. 1. Prediction of intake capacity, voluntary intake and milk production during lactation. *Grass and Forage Science* 66, 29-44.
- Fulkerson WJ, Davison TM, Garcia SC, Hough G, Goddard ME, Dobos R and Blockey M 2008. Holstein-Friesian Dairy Cows Under a Predominantly Grazing System: Interaction Between Genotype and Environment. *Journal of dairy science* 91, 826-839.
- Gill MS and Kaushal JR 2000. Feeding of grass silage to dairy cows with special reference to systems of concentrate feeding in United Kingdom - a review. *Agricultural Reviews* 21, 71-79.
- Grummer R, Hoffman P, Luck M and Bertics S 1995. Effect of prepartum and postpartum dietary energy on growth and lactation of primiparous cows. *Journal of dairy science* 78, 172-180.

- Horan B, Dillon P, Faverdin P, Delaby L, Buckley F and Rath M 2005. The Interaction of Strain of Holstein-Friesian Cows and Pasture-Based Feed Systems on Milk Yield, Body Weight, and Body Condition Score. *Journal of dairy science* 88, 1231-1243.
- Inchaisri C, Hogeveen H, Vos PLAM, van der Weijden GC and Jorritsma R 2010. Effect of milk yield characteristics, breed, and parity on success of the first insemination in Dutch dairy cows. *Journal of dairy science* 93, 5179-5187.
- Kennedy E, O'Donovan M, O'Mara FP, Murphy JP and Delaby L 2007. The Effect of Early-Lactation Feeding Strategy on the Lactation Performance of Spring-Calving Dairy Cows. *Journal of dairy science* 90, 3060-3070.
- Kennedy J, Dillon P, Delaby L, Faverdin P, Stakelum G and Rath M 2003. Effect of Genetic Merit and Concentrate Supplementation on Grass Intake and Milk Production with Holstein Friesian Dairy Cows. *Journal of dairy science* 86, 610-621.
- Lombard JE, Garry FB, Tomlinson SM and Garber LP 2007. Impacts of Dystocia on Health and Survival of Dairy Calves. *Journal of dairy science* 90, 1751-1760.
- McCarthy S, Horan B, Dillon P, O'Connor P, Rath M and Shalloo L 2007. Economic Comparison of Divergent Strains of Holstein-Friesian Cows in Various Pasture-Based Production Systems. *Journal of dairy science* 90, 1493-1505.
- McDougall S, Roberts K and Brownlie T 2012. Incalf: The new Zeland experience. In *Dairy Cow Fertility. Reproductive performance for efficient pasture-based systems* (Ed. DS Bulter), pp. 19-24. Cork.
- McEvoy M, Kennedy E, Murphy JP, Boland TM, Delaby L and O'Donovan M 2008. The Effect of Herbage Allowance and Concentrate Supplementation on Milk Production Performance and Dry Matter Intake of Spring-Calving Dairy Cows in Early Lactation. *Journal of dairy science* 91, 1258-1269.
- Mee JF, Berry DP and Cromie AR 2011. Risk factors for calving assistance and dystocia in pasture-based Holstein-Friesian heifers and cows in Ireland. *The Veterinary Journal* 187, 189-194.
- Miller RH, Kuhn MT, Norman HD and Wright JR 2008. Death Losses for Lactating Cows in Herds Enrolled in Dairy Herd Improvement Test Plans. *Journal of dairy science* 91, 3710-3715.
- Pryce JE, Coffey MP and Simm G 2001. The Relationship Between Body Condition Score and Reproductive Performance. *Journal of dairy science* 84, 1508-1515.
- Reis RB and Combs DK 2000. Effects of Increasing Levels of Grain Supplementation on Rumen Environment and Lactation Performance of Dairy Cows Grazing Grass-Legume Pasture. *Journal of dairy science* 83, 2888-2898.
- Robaina AC, Grainger C, Moate P, Taylor J and Stewart J 1998. Responses to grain feeding by grazing dairy cows. *Australian Journal of Experimental Agriculture* 38, 541-549.
- Roche JR, Berry DP and Kolver ES 2006. Holstein-Friesian Strain and Feed Effects on Milk Production, Body Weight, and Body Condition Score Profiles in Grazing Dairy Cows. *Journal of dairy science* 89, 3532-3543.
- Roche JR, Sheahan AJ, Chagas LM and Berry DP 2007. Concentrate Supplementation Reduces Postprandial Plasma Ghrelin in Grazing Dairy Cows: A Possible Neuroendocrine Basis for Reduced Pasture Intake in Supplemented Cows. *Journal of dairy science* 90, 1354-1363.
- Tozer PR, Bargo F and Muller LD 2004. The Effect of Pasture Allowance and Supplementation on Feed Efficiency and Profitability of Dairy Systems. *Journal of dairy science* 87, 2902-2911.